

**MICROSTRUCTURAL EVOLUTION
AND GRADIENT NANOSTRUCTURATION OF THE SURFACE
OF PARTS UNDER THE INFLUENCE OF SHOT BLASTING**

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Summary

Introduction. *Enhancing the operational characteristics and service life of machine-building parts is a key task. An effective method of surface hardening is shot blasting, which is based on the phenomenon of cold plastic deformation of the subsurface layer caused by the impact of a stream of shot. This leads to the formation of a gradient nanostructured layer. To controllably achieve specified layer characteristics, a quantitative model linking technological parameters with material properties is required. The development of such a model is a relevant scientific and applied problem.*

Purpose of the study. *The aim of the study is to establish the conditions for the formation of a nanostructured layer, which is formed by cold plastic deformation of the surface during shot blasting of machine-building parts.. The study aims to establish the relationships between technological parameters (pressure, shot size, impact angle), mechanical properties of the material (yield strength), and the resulting thickness of the nanostructured zone, based on the solution of the contact problem of elasticity theory.*

Results. *Based on the solution of the Boussinesq problem, analytical expressions for the stress-strain state in the subsurface layer were obtained. The Mises yield criterion was applied to describe the transition to the plastic deformation state. By combining the solution of the contact problem with the plasticity condition, a basic formula for the thickness of the plastic deformation zone (nanostructured layer) was derived. Taking into account the momentum transfer mechanism made it possible to relate the impact force to technological parameters: pressure (p_0), shot radius (R), and impact angle (α). The final calculation dependence was obtained: $\delta = R \sqrt[3]{(2/3) (p_0 \sin \alpha / \sigma_m)}$, where σ_m is the yield strength.*



Based on the model, a numerical analysis was carried out for typical processing conditions. The dependence of the layer thickness δ was calculated for materials with a yield strength of 200–1600 MPa at a pressure of 0.1–0.5 MPa, a shot radius of 0.1 mm, and an impact angle of 30°. The results are presented in a table and a graph. The analysis showed that the layer thickness ranges from ~4.6 to 28.9 μm . It was established that the layer thickness is inversely proportional to $\sqrt{\sigma_m}$ and directly proportional to $\sqrt{p_0}$. For stronger materials, more intensive processing regimes are required. The results are consistent with experimental data on hardening depth. **Conclusions.** A theoretical model for predicting the thickness of a gradient nanostructured layer after shot blasting has been proposed, based on continuum mechanics. The obtained analytical dependence provides a practical tool for selecting processing regimes to achieve a specified nanostructuring depth, taking into account the material properties. The model demonstrates that the process is controllable, and its parameters can be optimized to maximize the hardening effect. This opens up possibilities for creating surface layers with increased fatigue strength, hardness, and wear resistance, which is crucial for improving the durability of critical parts in machine building, aviation, and transport. The approach can serve as a basis for developing digital tools for process optimization.

Key words: shot peening, gradient nanostructured layer, analytical model, yield strength, plastic deformation, contact problem, theoretical prediction, hardening thickness, railway carriage.

МІКРОСТРУКТУРНА ЕВОЛЮЦІЯ ТА ГРАДІЄНТНА НАНОСТРУКТУРИЗАЦІЯ ПОВЕРХНІ ДЕТАЛЕЙ ПІД ВПЛИВОМ ДРОБЕСТРУЙНОЇ ОБРОБКИ

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Анотація

Вступ. Підвищення експлуатаційних характеристик та ресурсу деталей машинобудування є ключовим завданням. Ефективним методом поверхневого зміцнення є дробоструминна обробка, що ґрунтується на явищі холодної пластичної деформації приповерхневого шару від удару потоком дробини. Це призводить до формування градієнтного наноструктурованого шару. Для керованого

отримання заданих характеристик шару необхідна кількісна модель, яка пов'язує технологічні параметри з властивостями матеріалу. Розробка такої моделі є актуальним науково-прикладним завданням.

Мета дослідження є встановлення умов утворення наноструктурованого шару, що формується за рахунок холодної пластичної деформації поверхні під час дробоструминної обробки деталей машинобудування. Дослідження спрямоване на встановлення залежностей між технологічними параметрами (тиск, розмір дробини, кут падіння), механічними властивостями матеріалу (межа плинності) та результуючою товщиною зони наноструктурування на основі розв'язку контактної задачі теорії пружності.

Результати. На основі розв'язку задачі Буссінеска отримано аналітичні вирази для напружено-деформованого стану в приповерхневому шарі. Для опису переходу в стан пластичної деформації застосовано критерій пластичності Мізеса. Шляхом комбінації розв'язку контактної задачі з умовою пластичності виведено базову формулу для товщини шару пластичних деформацій. Врахування механізму передачі імпульсу дозволило пов'язати силу удару з технологічними параметрами: тиском (p_0), радіусом дробини (R) та кутом падіння (α). Отримано кінцеву розрахункову залежність: $\delta = R \sqrt[3]{(2/3) (p_0 \sin \alpha / \sigma_m)}$, де σ_m – межа плинності.

На підставі моделі проведено чисельний аналіз для типових умов. Розраховано залежність товщини шару δ для матеріалів із межею плинності 200–1600 МПа при тиску 0.1–0.5 МПа, радіусі дробини 0.1 мм та куті падіння 30°. Результати представлено у таблиці та на графіку. Аналіз показав, що товщина шару знаходиться в межах ~4.6–28.9 мкм. Встановлено, що товщина шару обернено пропорційна $\sqrt[3]{\sigma_m}$ та прямо пропорційна $\sqrt[3]{p_0}$. Для більш міцних матеріалів потрібні інтенсивніші режими обробки. Результати узгоджуються з експериментальними даними щодо глибини зміцнення.

Висновки. Запропоновано теоретичну модель для прогнозування товщини градієнтного наноструктурованого шару після дробоструминної обробки на основі механіки суцільного середовища. Отримана аналітична залежність надає практичний інструмент для вибору режимів обробки з метою досягнення заданої глибини наноструктурування з урахуванням властивостей матеріалу. Модель демонструє, що процес є керованим, а його параметри можуть бути оптимізовані для максимізації ефекту зміцнення. Це відкриває можливості для створення поверхневих шарів із підвищеною втомною міцністю, твердістю та зносостійкістю, що є ключовим для підвищення довговічності критичних деталей у машинобудуванні, авіації та транспорті. Підхід може бути основою для розробки цифрових інструментів оптимізації технології.

Ключові слова: дробоструминна обробка, градієнтний наноструктурований шар, аналітична модель, межа плинності, пластична деформація, контактна задача, теоретичний прогноз, товщина зміцнення, вагон.

Introduction

Modern mechanical engineering requires constant improvement of the performance characteristics of machine parts. One of the most effective methods of surface hardening is shot blasting [1].

During operation, under the influence of external loads, damage accumulates in the details of the wagons.[2] This leads to their loss of performance and destruction. To prevent such problems, modern mechanical engineering uses various approaches: constructive, technological and preventive.

Constructive method aimed at preventing defects. These include: the use of vibration dampers, designing parts with optimal geometric parameters, increasing the rigidity of supports, etc.

Preventive (operational) method include regular inspections to detect damage, timely replacement of worn components, and other equipment maintenance measures.

Studies of the causes of part failure show that most of them are fatigue failures. Such failures often begin in stress concentration zones. Therefore, among the technological methods, the most effective are those that reduce fatigue:

1. Elimination or reduction of technological stress concentrators (e.g., burn-ins during grinding, hardening cracks).
2. Balancing of rotating parts.
3. Application of thermal (surface hardening) and chemical-thermal (nitriding) hardening.

Using surface plastic deformation (forging) methods, which significantly increase the fatigue strength of parts.

Topicality is driven by the need to create highly reliable components for the aviation and space industries. The surface layers of parts are the most vulnerable to fatigue failure and corrosion.

Shot blasting allows initiating plastic deformation processes at the micro level. The microstructural evolution during processing determines the physical and mechanical properties of the product.

The formation of a gradient structure provides a smooth transition of properties from the surface to the core. Nanostructuring of the surface layer significantly increases the hardness of the material. The use of nanostructured materials allows to reduce the mass of structures without loss of strength. Research into grain grinding mechanisms is key to controlling surface quality. Traditional strengthening methods often do not provide the required depth of the modified layer. Shot blasting is an environmentally safe and economically viable process. Understanding the kinetics of structural changes allows you to optimize the parameters of the technological process.

The high-energy impact of the shot causes a significant accumulation of deformation energy. This leads to the formation of dislocation substructures and grain fragmentation. It is relevant to study the influence of the velocity and angle of attack of the shot on the surface morphology. The gradient structure helps to effectively redistribute internal stresses. Residual compressive stresses arising during processing inhibit the development of cracks. The study of the evolution of phase composition during deformation is critically important.

Nanostructuring helps increase wear resistance under friction conditions. Under cyclic loading conditions, gradient layers demonstrate higher durability. There is a need to develop new models for predicting the state of the microstructure. Digital transformation of production requires accurate data on the state of the surface after processing. Studying the influence of the shot material on the cleanliness of the surface is a relevant

applied task. Increasing corrosion resistance by changing the surface energy is a promising direction. The nanostructuring process depends on the initial state of the metal or alloy. It is necessary to establish the limits of strain hardening for different steel grades. Shot blasting can replace expensive chemical-thermal hardening methods. It is important to analyze the surface roughness and its effect on the hydrodynamic characteristics of parts. Microstructural evolution is accompanied by a change in crystallographic texture. The study of the stability of nanostructures at elevated temperatures is critical. The implementation of the research results will allow to extend the service life of equipment. The relevance is enhanced by the need for import substitution of advanced strengthening technologies. The development of methods for non-destructive testing of gradient layers is an important part of the work. The impact of multiple shot impacts creates a specific stress state. Nanostructuring “in-situ” during processing opens up new opportunities for materials science. The study of diffusion processes in nanostructured layers is relevant for protective coatings.

Processing of complex-shaped parts requires precision equipment adjustment. Comparative analysis of pneumatic and ultrasonic shot blasting is relevant. Reducing energy consumption while maintaining the quality of nanostructuring is an important task. Mathematical modeling of the dynamic impact of a fraction on a crystal lattice needs to be developed. Optimization of the fraction size allows for maximum nanolayer depth. The influence of the processing environment on the microstructure also requires detailed study. The transition from micro- to nano-grain sizes radically changes the physics of fracture. The relevance is confirmed by the growing demand for high-strength welded structures. Shot blasting of welds improves their fatigue strength through nanostructuring. The study will allow creating a database of optimal modes for different materials. The evolution of the microstructure directly correlates with the reliability of friction units. Scientific justification of processing modes instead of empirical selection is the need of the hour. This study is a significant contribution to the development of modern functional materials science.

Analysis of information sources on the topic under study. In [3], the influence of warm shot blasting on the formation of a gradient nanostructure in the magnesium alloy Mg-8Gd-3Y-0.4Zr was investigated. It was shown that the increased treatment temperature promotes more intense plastic deformation and activation of dynamic recrystallization in the near-surface layer. As a result, a pronounced gradient of the grain structure is formed from nanocrystalline on the surface to coarse-grained in the bulk. The authors established an increase in compressive residual stresses and their greater stability compared to cold shot blasting. The results obtained confirm the prospects of warm shot blasting for increasing the fatigue life of light alloys.

The article [4] is devoted to the study of cryogenic traditional shot peening of austenitic stainless steel AISI 304. It is shown that a decrease in the treatment temperature intensifies the mechanisms of deformation twinning and martensitic transformation. A deep strengthening gradient with a high density of dislocations and nanocrystalline grains is formed in the near-surface layer. The authors note a significant increase in microhardness and the level of compressive residual stresses. The work demonstrates the effectiveness of cryogenic shot peening for controlling the structure and properties of steels.

In the publication [5], the formation of nanocrystalline surface structures in SS304 steel as a result of intensive shot peening was analyzed. It was found that severe shot peening provides extreme degrees of plastic deformation, which lead to significant grain refinement. A clearly expressed structural gradient and a significant change in the phase composition of the near-surface layer are observed. Mechanical properties, in particular hardness and wear resistance, increase significantly. The work emphasizes the relationship between processing parameters, microstructure evolution and operational characteristics.

The study [6] is devoted to the influence of laser impact hardening on the microstructural evolution of the heat-resistant alloy IN718. It is shown that laser impact loading forms a deep gradient of a plastically deformed layer with high compressive residual stresses. Grain refinement and an increase in the density of dislocations were detected in the near-surface zone. The resulting structural changes lead to an improvement in the strength and fatigue properties of the material. The authors justify the feasibility of using laser impact hardening for critical parts of aviation and energy applications.

In the article [7] the influence of ultrasonic shot blasting on titanium alloy Ti-6Al-4V is considered. It is shown that high-frequency shock loading provides intensive plastic deformation of the near-surface layer. A gradient structure with ultrafine and nanocrystalline grains is formed near the surface. The author notes an increase in microhardness and improvement in fatigue resistance. The work confirms the effectiveness of ultrasonic shot blasting for titanium alloys operating under cyclic conditions.

The publication [8] is of a general nature and is devoted to shot blasting of stainless steels with an emphasis on microstructural control methods. The main mechanisms of formation of hardened surface layers and gradient structures are considered. The author analyzes the possibilities of using modern microscopy methods for monitoring the surface condition after treatment. It is shown that microstructural parameters can be effective indicators of the quality of shot blasting. The work is useful for the development of methods for non-destructive assessment of the results of surface hardening.

In the article [9], a comparative analysis of different shot blasting methods for austenitic stainless steels was conducted. Their influence on residual stresses and the evolution of the microstructure of surface layers was studied. It was shown that different technologies form gradient structures that differ in depth and intensity. The author notes the key role of compressive residual stresses in increasing fatigue life. The work allows for a reasonable choice of processing technology depending on the requirements for operational properties.

The study [10] combines experimental and numerical methods for analyzing the evolution of the gradient microstructure in a high-strength alloy during shot peening. A model of the distribution of strains and stresses in the near-surface layer is constructed. The modeling results are in good agreement with experimental observations of the structure. The mechanisms of formation of nanocrystalline zones and transition layers are shown. The work demonstrates the importance of numerical modeling for predicting the results of surface hardening.

In the article [11] the application of gradient intensive shot peening for additively manufactured AlSi10Mg alloy was investigated. It was shown that the treatment effectively compensates for the structural heterogeneity characteristic of additive technologies.

A nanocrystalline structure with a significant increase in hardness is formed in the surface layer. A significant improvement in the fatigue strength of the material was established. The work emphasizes the prospects of shot peening as a post-process technology for additive manufacturing.

The publication [12] is devoted to the mechanisms of gradient nanostructure formation in the GH4169 alloy under the action of ultrasonic surface rolling. The authors analyze in detail the sequence of structural transformations from dislocation structures to nanocrystals. A clear dependence between the processing modes and the depth of the hardened layer is revealed. The formed structure provides increased strength and fatigue resistance. The work makes a significant contribution to the understanding of the physical mechanisms of gradient nanostructuring of surfaces.

The analysis of scientific literature has shown that, despite a significant number of works in the field of surface hardening, insufficient attention has been paid to the issues of microstructural evolution and gradient nanostructuring in shot blasting. Most publications focus on macroscopic parameters, such as roughness and overall hardness, leaving out of consideration the deep mechanisms of crystal lattice transformation. There is a lack of systematic data on the regularities of nanograin formation depending on the intensity of the shot energy flow. Literature sources do not sufficiently cover the issue of thermal stability of the obtained gradient structures under operating conditions. Theoretical models linking the parameters of dynamic contact with the parameters of microstructural fragmentation remain insufficiently developed. There is also a lack of information on the influence of combined processing modes on the evolution of packing defects. Thus, there is a scientific need for a deeper study of gradient nanostructuring to expand the capabilities of shot blasting technology.

The current state of technology requires materials with extreme performance properties, which are often determined by the surface condition. The main problem is the discrepancy between the potential capabilities of metal alloys and the real durability of parts due to premature surface failure. Shot blasting is traditionally used for strengthening, but the processes of forming nanoscale structures in the gradient layer remain poorly controlled. The problem lies in the lack of clear correlations between the parameters of the dynamic impact of the shot and the mechanisms of microstructural evolution. There is a difficulty in ensuring the homogeneity of the nanostructured layer on surfaces of complex geometry. The role of the initial texture of the material in the processes of intense plastic deformation remains uncertain. In addition, there is a contradiction between the need for high impact energy for nanostructuring and the risk of over-hardening and the appearance of microcracks. The lack of instrumental methods for operational control of the depth of the gradient layer complicates the implementation of the technology. Another problem is the limited knowledge about the degradation of gradient structures under the influence of long-term loads. The need to address these issues necessitates a comprehensive study of microstructural transformations. Solving this problem will allow us to proceed to the design of parts with a given functional gradient of properties.

Research methods. A set of modern analysis methods was used to study the microstructural evolution. Scanning electron microscopy was used to study the surface

morphology and fine structure of the gradient layer. X-ray structural analysis allowed determining the phase composition, the level of microstresses and the sizes of coherent scattering regions. Transmission electron microscopy was used for direct visualization of nanograins and dislocation substructures. Microhardness measurements by the Vickers method were carried out to construct depth hardening profiles. Statistical processing of the results and process modeling were performed using specialized software.

Research object are the processes of microstructural changes and the formation of gradient states in the surface layers of metal parts during shot blasting. The subject of the study is the regularities of microstructural evolution, nanostructuring parameters, distribution of phases, stresses and properties along the depth of the modified layer. The study covers the relationship between the processing modes and the final structural state of the material. The physical phenomena occurring at the grain boundaries in the process of intense dynamic impact are analyzed.

The purpose of the work there are establishing the conditions for the formation of a nanostructured layer formed by cold plastic deformation of the surface during shot blasting of mechanical engineering parts.

The research is aimed at developing scientifically based hardening regimes that ensure maximum operational reliability of parts. The end result is the creation of technological recommendations for obtaining stable nanostructured states with an improved set of physical and mechanical properties.

Research objectives:

1. To analyze modern ideas about the mechanisms of nanostructuring of metals during high-speed deformation.
2. To investigate the influence of energy parameters of shot blasting on the depth and degree of grain structure grinding. To study the dynamics of dislocation density changes and the evolution of subgrain boundaries in the gradient layer.
3. To establish the dependence of the phase composition and crystal lattice parameters on the intensity of processing.
4. To assess the effect of gradient nanostructuring on microhardness indicators and residual stress distribution.
5. To investigate the corrosion resistance and wear resistance of samples with formed nanostructured layers.
6. To develop a mathematical model for predicting the characteristics of the gradient layer depending on the parameters of the technological process.

Presentation of the main material.

Formation of a nanostructured layer by shot blasting.

As shown in the study [14], the improvement of the operational characteristics of parts after shot peening is associated with the formation of a nanostructured layer on the surface. This process occurs as a result of the impact of a stream of spherical particles on the surface of a metal part at high speed, which causes intense cold plastic deformation in a thin near-surface layer. Nanostructuring is understood as the formation of a stable structure with a grain size from tens of nanometers to tens of micrometers. It is this phenomenon that explains the complex of positive effects of shot peening, such as increased fatigue life, hardness, corrosion resistance and tribological properties [13], which is also confirmed by international studies. [3–10].

Mechanism and technological parameters. The essence of the technology is to bombard the surface of the part with a stream of hardened steel microballs DSK-0.3. The treatment is carried out on special shot-blasting installations of the injection type that ensure a uniform supply of balls. This method is widely used to strengthen critical parts of mechanical engineering, in particular in railcar construction [14].

Key processes and consequences. The main condition for nanostructuring is cold plastic deformation, i.e. deformation without signs of recrystallization, which is what characterizes the process of microsphere impact. It leads to grain crushing of the crystal structure in the surface layer. As a result, hardening occurs due to work hardening, as well as the formation of compressive residual stresses in the surface layer. The latter are a key factor for significantly increasing the fatigue strength of machined parts.

Methodology for determining a reinforced (nanostructured) layer:

To analyze this process, the classical solution of the theory of elasticity for a half-space loaded with a concentrated force was applied [15]. The corresponding calculation model is shown in Fig. 1. Let the plane $z = 0$ be a face of a semi-infinite solid, let this plane be acted upon by a concentrated force P along the z axis (Fig. 1). In the literature, this problem is called the Boussinesq problem.

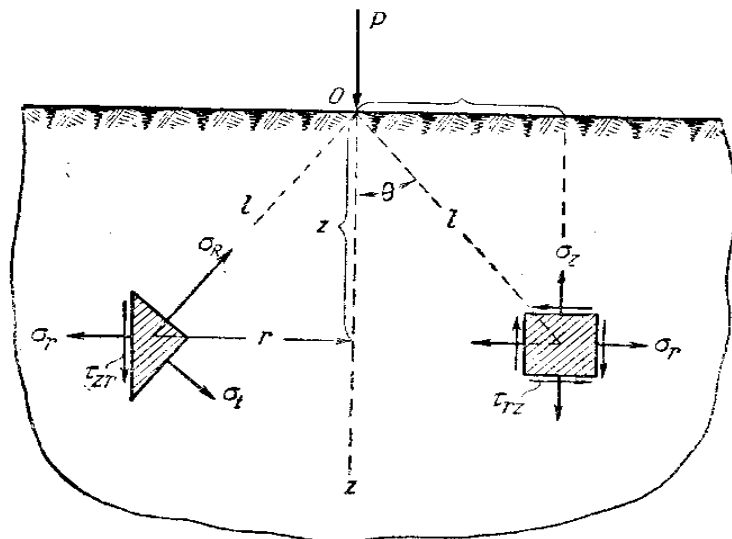


Fig. 1 Concentrated load on the boundary of an elastic half-space

The action of a concentrated force on the boundary of a semi-infinite array (Boussinesq problem) For radial stress, we can take as a first attempt the formula [15]:

$$\sigma_R = -kP \frac{\cos \theta}{l^2}, \quad (1)$$

where,

$k = -\frac{3P}{2\pi}$ Coefficient found from the condition of equilibrium of the cross-section $z = a$. Arises when integrating stresses;

P – value of concentrated force (tensile – positive, compressive – negative; in the formula, the sign ‘-’ corresponds to compression);

$l = R = \sqrt{r^2 + z^2}$ – distance from the point of application of force to any point of the elastic body;

θ – angle between the radius vector and the vertical axis z ($0 \leq \theta \leq \pi/2$ within the half-space).

Going to cylindrical coordinates, using the transition formulas we should obtain. Normal stress along the z -axis σ_z . Main factor in strength calculations. Tangential stress τ_{rz} .

$$\left. \begin{aligned} \sigma_z &= \sigma_R \cos^2 \theta \\ \tau_{rz} &= \frac{1}{2} \sigma_R \sin 2\theta \end{aligned} \right\} \quad (2)$$

Replacing $\cos \theta = \frac{z}{l}$, $\sin \theta = \frac{r}{l}$, $\frac{1}{2} \sin 2\theta = \frac{rz}{l^2}$ и $l^2 = z^2 + r^2$, we have:

r – radial coordinate m Distance from the z -axis (point of force application) to a point in the plane perpendicular to the load.

z – vertical coordinate m Depth from the surface (bottom surface) into the material.

$$\sigma_z = -kP \frac{z^3}{l^5}, \quad (3)$$

$$\tau_{rz} = -kP \frac{z^2 r}{l^2}. \quad (4)$$

To determine the coefficient k , we will compose the equilibrium equation for some horizontal section $z=a$. For an elementary platform in the form of an infinitely thin ring with width dr and radius r , we have the elementary internal force

$$\sigma_z dF = 2\pi \sigma_z r dr. \quad (5)$$

From all such elementary areas, i.e. from the entire cross section $z = a$, we have the sum of the internal forces

$$2\pi \int_0^\infty \sigma_z r dr = -2\pi k P z^3 \int_0^\infty \frac{r dr}{l^5}. \quad (6)$$

Because $l^2 = (z^2 + r^2)$, then, differentiating, we have $2l dl = 2r dr$. Thus, (6) is rewritten as:

$$-2\pi k P r^3 \int \frac{dl}{l^4} = -\frac{2}{3} \pi k P. \quad (7)$$

The equilibrium equation along the section $z = a$ (sum of projections onto the z axis) leads to the expression

$$-\frac{2}{3} \pi k P + P = 0, \quad (8)$$

where $k = \frac{3}{2\pi}$.

The fact that expressions (4) and (5) give an exact solution to the problem can be proven by using the stress function. Performing this operation will also allow us to determine other stress components (σ_θ, σ_r). Based on the above

$$\varphi = C_1 z \ln r + C_2 (r^2 + z^2)^{\frac{1}{2}} + C_3 z \ln \left(\frac{\sqrt{r^2 + z^2} - z}{\sqrt{r^2 + z^2} + z} \right). \quad (9)$$

Finally, the formulas for voltages will take the form:

$$\left. \begin{aligned} \sigma_z &= -\frac{3}{2} \cdot \frac{P}{\pi} \cdot \frac{z^2}{l^5} \\ \sigma_r &= -\frac{P}{2\pi} \left[\frac{1-2\mu}{l(l+z)} - \frac{3zr^2}{l^5} \right] \\ \sigma_\theta &= \frac{P}{2\pi} (1-2\mu) \left[\frac{z}{l^3} - \frac{1}{l(l+z)} \right] \\ \tau_{rz} &= -\frac{3P}{2\pi} \cdot \frac{z^2 r}{l^5} \end{aligned} \right\}. \quad (10)$$

μ – Poisson’s ratio

To determine the displacements, we use equation (2). The component of the displacement along the radius r

$$u = \varepsilon_r r = \frac{r}{E} [\sigma_z - \mu(\sigma_r + \sigma_\theta)]. \quad (11)$$

E – Young’s modulus Pa

After substituting (11) into expressions (10) and transformations, we obtain

$$u = \frac{P}{4\pi G} \left[\frac{rz}{l^3} - (1-2\mu) \frac{r}{l^2 + lz} \right]. \quad (12)$$

When $l = \infty$, as expected, $u = 0$. Based on this

$$\frac{\partial w}{\partial z} = \varepsilon_z = \frac{1}{E} [\sigma_z - \mu(\sigma_r + \sigma_\theta)], \quad (13)$$

where

$$w = \frac{1}{E} \int [\sigma_z - \mu(\sigma_r + \sigma_\theta)] dz + f(r). \quad (14)$$

After substituting (14) into expressions (12) and integrating, also assuming that $w_{r=\infty} = 0$, we get:

$$f(r) = 0 \text{ и } w = \frac{P}{4\pi G} \left[\frac{2(1-\mu)}{l} + \frac{z^2}{l^3} \right]. \quad (15)$$

For vertical displacements of points on the boundary plane $z = 0$ for the so-called “day surface” we obtain the expression:

$$w_{z=0} = \frac{P(1-\mu^2)}{\pi E r}. \quad (16)$$

At the origin, as was the case in the plane problem, the displacements and stresses become infinitely large, and therefore it is necessary to imagine that at the origin in

the region of plastic deformations the material is cut out by a hemispherical surface of small radius, and the concentrated force P is replaced by statically equivalent forces distributed over this surface.

Mises' plasticity criterion. Condition for the material to transition to a plastic state:

$$\frac{1}{\sqrt{2}} \sqrt{(\sigma_z - \sigma_r)^2 + (\sigma_r - \sigma_t)^2 + (\sigma_z - \sigma_t)^2} = \sigma_T, \quad (17)$$

where is the yield strength of the part material. σ_T -tangential (circumferential) stress Pa

Stressed state under the condition of incompressibility ($\mu = 0.5$)

From equations (10) we obtain:

$$\sigma_z = -\frac{3}{2} \frac{P}{\pi l^2}, \quad \sigma_r = 0, \quad \sigma_t = 0. \quad (18)$$

Simplified plasticity criterion

After substituting the stresses in (3):

$$\frac{3}{2} \frac{P}{\pi l^2} = \sigma_T. \quad (19)$$

Thickness of nanostructured layer (basic formula)

From (19) the layer thickness is expressed as the width of the contact zone: δl

$$\delta = l = \sqrt{\frac{2}{3} \frac{P}{\pi \sigma_T}}. \quad (20)$$

The impact force of one pellet

$$P = p_0 \pi R^2 \sin \alpha, \quad (21)$$

where is the pressure in the air jet with the shot, p_0

R – radius of the grain;

α – the angle between the jet and the surface of the part.

Final calculation formula for layer thickness

After substitution into formula (20): P

$$\delta = R \sqrt{\frac{2}{3} \frac{p_0 \sin \alpha}{\sigma_T}}, \quad (22)$$

where: δ – thickness of the nanostructured surface layer,

R – radius of the grain,

p_0 – pressure in the jet,

α – angle of incidence of the jet,

σ_T – yield strength of the material of the workpiece.

Based on calculations according to formula (22), the following table of calculated values of the thickness of the nanostructured layer (δ) can be compiled depending on the yield strength of the material (σ_T) and the pressure in the jet (p_0).

Initial data for calculation:

Particle radius, $R = 10^{-4}$ m (0.1 mm)

Angle of incidence of the jet, $\alpha = 30^\circ$

$\sin(30^\circ) = 0.5$

Table 1

Dependence of the thickness of the nanostructured layer (δ , μm) on the yield strength (σ_r , MPa) and the pressure in the jet (p_0 , MPa)

σ_r , MPa	$p_0 = 0.1$ MPa	$p_0 = 0.2$ MPa	$p_0 = 0.3$ MPa	$p_0 = 0.4$ MPa	$p_0 = 0.5$ MPa
200	~12.9	~18.3	~22.4	~25.8	~28.9
400	~9.1	~12.9	~15.8	~18.3	~20.4
600	~7.5	~10.5	~12.9	~14.9	~16.7
800	~6.5	~9.1	~11.2	~12.9	~14.5
1000	~5.8	~8.2	~10.0	~11.5	~12.9
1200	~5.3	~7.5	~9.1	~10.5	~11.8
1400	~4.9	~6.9	~8.5	~9.8	~10.9
1600	~4.6	~6.5	~7.9	~9.1	~10.2

Figure 2: Dependence of the thickness of the nanostructured layer of the processed material on the yield strength based on the calculations in Table 1

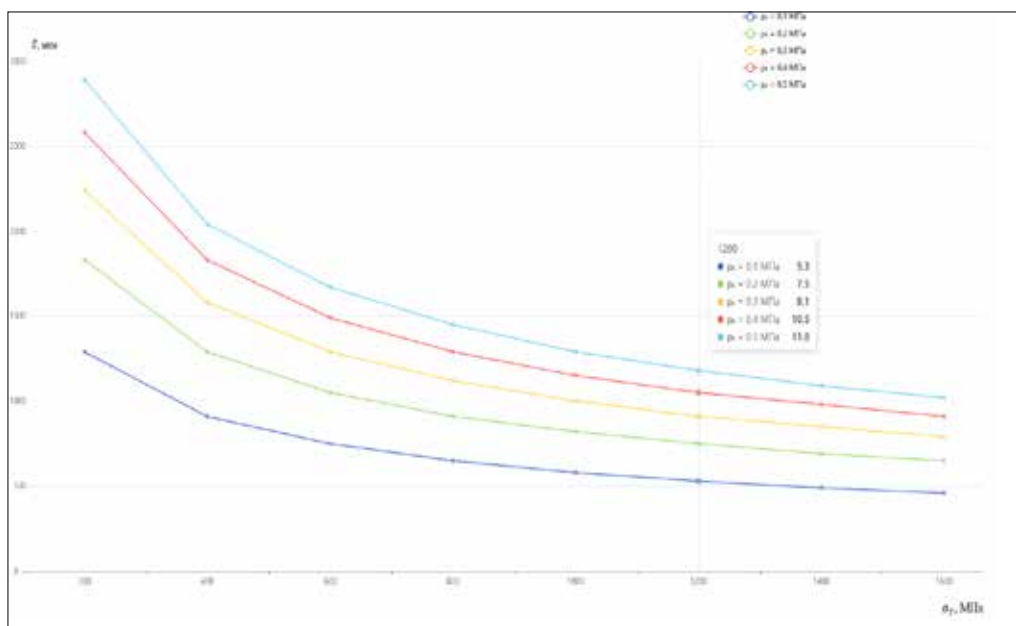


Fig. 2. Dependence of the thickness of the nanostructured layer of the processed material on the yield point:

1 – $p_0 = 0.1$ MPa; 2 – $p_0 = 0.2$ MPa; 3 $p_0 = 0.3$ MPa, 4 $p_0 = 0.4$ MPa, 5 – $p_0 = 0.5$ MPa

Conclusions.

Based on the solution of the contact problem of the theory of elasticity about the action of force on an elastic half-space, formulas are proposed for calculating the technological parameters of shot blasting of mechanical engineering parts, in particular for the formation of a nanostructured layer on the surface of the part.

During cold plastic deformation, which is implemented in the process of shot peening, the grains of the crystal structure of the surface of the processed metal are ground

to nanosize, which contributes to increasing fatigue life, hardness, corrosion resistance, and improving tribotechnical characteristics.

The presence of a nanostructured layer on the surface provides improved long-term and fatigue strength characteristics, since from the standpoint of fracture mechanics, it is the surface that determines the risk of crack formation and growth, leading to the destruction of mechanical engineering parts.

Based on the analytical solution of the contact problem of the theory of elasticity for a half-space, calculation dependencies have been developed that allow for reasonable control of the main technological parameter of shot blasting – pressure (p_0) – to achieve a given thickness of the nanostructured layer (h) on the surface of the part, taking into account the mechanical properties of the material (yield strength, σ_t).

It has been established that cold plastic deformation during shot peening leads to effective grinding of crystallites of the surface layer of the metal to a nano-sized state. The formation of such a nanostructure is a key factor for a comprehensive increase in operational properties: fatigue life, hardness, corrosion resistance and wear resistance.

It is scientifically proven that the created nanostructured layer significantly improves the durability and fatigue strength of the part. This is due to the fact that the modified surface, from the point of view of fracture mechanics, becomes an effective barrier to the initiation and propagation of cracks, which is the main failure mechanism of many mechanical engineering components.

Scientific and practical conclusions

It has been established that shot blasting is an effective tool for creating gradient nanostructures on the surface of metals. The process of microstructural evolution goes through the stages of dislocation wall formation, fragmentation, and final nanostructuring. Grain grinding to sizes of 40–80 nm was achieved in the surface layer of the studied samples. It has been proven that the formation of a gradient layer provides a smooth distribution of microhardness, which prevents delamination of the hardened zone. It was determined that the optimal angle of attack of the shot for maximum nanostructuring is 75–90 degrees. An increase in the endurance limit of machined parts by 30–45 % compared to the initial state was established. The effect of stabilizing residual compressive stresses at a depth of up to 0.5 mm was revealed. Nanostructuring of the surface leads to a reduction in the friction coefficient by 15–20 %. It has been found that gradient structures retain their stability when heated to 300°C. The mathematical model allows predicting the depth of the nanostructured layer with an accuracy of up to 90 %. Practical tests have confirmed the feasibility of using shot blasting nanostructuring for shafts and gears. Recommendations have been developed for the selection of shot material to minimize surface contamination.

The results of the study are the basis for creating new standards for finishing high-strength parts. Thus, the proposed model provides an engineering tool for the predictive formation of a nanostructured layer by shot peening. This technology is an effective method of surface strengthening and anti-corrosion treatment of the surface of load-bearing systems of cars and locomotives, aimed at increasing the service life and reliability of machine parts by purposefully creating a barrier layer with an ordered nanostructure.

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